Compiler Construction

Lecture 4: Lexical Analysis III (Practical Aspects)

Thomas Noll

Lehrstuhl für Informatik 2
(Software Modeling and Verification)

RWTH Aachen University

noll@cs.rwth-aachen.de

http://www-i2.informatik.rwth-aachen.de/i2/cc12/

Summer Semester 2012

Outline

The Extended Matching Problem I

Definition

Let $n \geq 1$ and $\alpha_1, \ldots, \alpha_n \in RE_\Omega$ with $\varepsilon \notin [\![\alpha_i]\!] \neq \emptyset$ for every $i \in [n]$ $(= \{1, \ldots, n\})$. Let $\Sigma := \{T_1, \ldots, T_n\}$ be an alphabet of corresponding tokens and $w \in \Omega^+$. If $w_1, \ldots, w_k \in \Omega^+$ such that

- $w = w_1 \ldots w_k$ and
- for every $j \in [k]$ there exists $i_j \in [n]$ such that $w_j \in [\![\alpha_{i_j}]\!]$,

then

- $(w_1, \ldots, w_k)$ is called a decomposition and
- $(T_{i_1}, \ldots, T_{i_k})$ is called an analysis

of w w.r.t. $\alpha_1, \ldots, \alpha_n$.

Problem (Extended matching problem)

Given $\alpha_1, \ldots, \alpha_n \in RE_\Omega$ and $w \in \Omega^+$, decide whether there exists a decomposition of w w.r.t. $\alpha_1, \ldots, \alpha_n$ and determine a corresponding analysis.

Ensuring Uniqueness

Two principles:

1. Principle of the longest match (“maximal munch tokenization”)
   - for uniqueness of decomposition
   - make lexemes as long as possible
   - motivated by applications: e.g., every (non-empty) prefix of an identifier is also an identifier
2. Principle of the first match
   - for uniqueness of analysis
   - choose first matching regular expression (in the given order)
   - therefore: arrange keywords before identifiers (if keywords protected)

Implementation of FLM Analysis

Algorithm (FLM analysis—overview)

Input: *expressions* $\alpha_1, \ldots, \alpha_n \in RE_\Omega$, *tokens* $\{T_1, \ldots, T_n\}$, *input word* $w \in \Omega^+$

Procedure:

1. *for every* $i \in [n]$, *construct* $\mathfrak{A}_i \in DFA_\Omega$ *such that* $L(\mathfrak{A}_i) = [\![\alpha_i]\!]$ *(see DFA method; Alg. 2.9)*
2. *construct the product automaton* $\mathfrak{A} \in DFA_\Omega$ *such that* $L(\mathfrak{A}) = \bigcup_{i=1}^{n} [\![\alpha_i]\!]$
3. *partition the set of final states of* $\mathfrak{A}$ *to follow the first-match principle*
4. *extend the resulting DFA to a backtracking DFA which implements the longest-match principle, and let it run on* w

Output: *FLM analysis of* w *(if existing)*

(4) The Backtracking DFA

Definition (Backtracking DFA)

- The set of configurations of $\mathfrak{B}$ is given by

$$(\{N\} \uplus \Sigma) \times \Omega^* \cdot Q \cdot \Omega^* \times \Sigma^* \cdot \{\varepsilon, \mathrm{lexerr}\}$$

- The initial configuration for an input word $w \in \Omega^+$ is $(N, q_0 w, \varepsilon)$.
- The transitions of $\mathfrak{B}$ are defined as follows (where $q' := \delta(q, a)$):
  - normal mode: look for a match

$$(N, qaw, W) \vdash \begin{cases} (T_i, q'w, W) & \text{if } q' \in F^{(i)} \\ (N, q'w, W) & \text{if } q' \in P \setminus F \\ \textbf{output: } W \cdot \mathrm{lexerr} & \text{if } q' \notin P \end{cases}$$

  - backtrack mode: look for longest match

$$(T, vqaw, W) \vdash \begin{cases} (T_i, q'w, W) & \text{if } q' \in F^{(i)} \\ (T, vaq'w, W) & \text{if } q' \in P \setminus F \\ (N, q_0 vaw, WT) & \text{if } q' \notin P \end{cases}$$

  - end of input

$$\begin{aligned} (T, q, W) &\vdash \textbf{output: } WT & \text{if } q \in F \\ (N, q, W) &\vdash \textbf{output: } W \cdot \mathrm{lexerr} & \text{if } q \in P \setminus F \\ (T, vaq, W) &\vdash (N, q_0 va, WT) & \text{if } q \in P \setminus F \end{aligned}$$

Outline

A Backtracking NFA

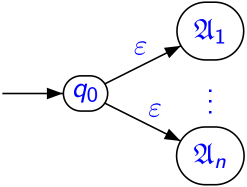
A similar construction is possible for the NFA method:

1. $\mathfrak{A}_i = \langle Q_i, \Omega, \delta_i, q_0^{(i)}, F_i \rangle \in NFA_\Omega$ $(i \in [n])$ by NFA method

A Backtracking NFA

A similar construction is possible for the NFA method:

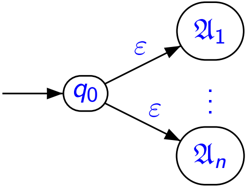
1. $\mathfrak{A}_i = \langle Q_i, \Omega, \delta_i, q_0^{(i)}, F_i \rangle \in NFA_\Omega$ ($i \in [n]$) by NFA method
2. "Product" automaton: $Q := \{q_0\} \uplus \biguplus_{i=1}^{n} Q_i$



A Backtracking NFA

A similar construction is possible for the NFA method:

1. $\mathfrak{A}_i = \langle Q_i, \Omega, \delta_i, q_0^{(i)}, F_i \rangle \in NFA_\Omega$ ($i \in [n]$) by NFA method
2. "Product" automaton: $Q := \{q_0\} \uplus \biguplus_{i=1}^{n} Q_i$

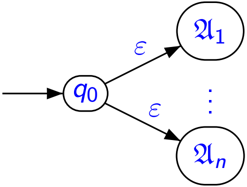


3. Partitioning of final states:
   - $M \subseteq Q$ is called a T_i-matching if
     $$M \cap F_i \neq \emptyset \text{ and for all } j \in [i-1] : M \cap F_j = \emptyset$$
   - yields set of T_i-matchings $F^{(i)} \subseteq 2^Q$
   - $M \subseteq Q$ is called productive if there exists a productive $q \in M$
   - yields productive state sets $P \subseteq 2^Q$

A Backtracking NFA

A similar construction is possible for the NFA method:

1. $\mathfrak{A}_i = \langle Q_i, \Omega, \delta_i, q_0^{(i)}, F_i \rangle \in NFA_\Omega$ $(i \in [n])$ by NFA method
2. "Product" automaton: $Q := \{q_0\} \uplus \biguplus_{i=1}^n Q_i$



3. Partitioning of final states:
   - $M \subseteq Q$ is called a T_i-matching if

$$M \cap F_i \neq \emptyset \text{ and for all } j \in [i-1] : M \cap F_j = \emptyset$$

   - yields set of T_i-matchings $F^{(i)} \subseteq 2^Q$
   - $M \subseteq Q$ is called productive if there exists a productive $q \in M$
   - yields productive state sets $P \subseteq 2^Q$
4. Backtracking automaton: similar to DFA case

Outline

Longest Match in Practice

- In general: lookahead of arbitrary length required
  - that is, $|v|$ unbounded in configurations (T, vqw, W)
  - see Example 3.19: $\alpha_1 = a$, $\alpha_2 = a^*b$, $w = a \ldots a$

Longest Match in Practice

- In general: lookahead of arbitrary length required
  - that is, $|v|$ unbounded in configurations (T, vqw, W)
  - see Example 3.19: $\alpha_1 = a$, $\alpha_2 = a^*b$, $w = a \dots a$
- "Modern" programming languages (Pascal, Java, ...): lookahead of one or two characters sufficient
  - separation of keywords, identifiers, etc. by spaces
  - Pascal: two-character lookahead required to distinguish `1.5` (real number) from `1..5` (integer range)

Longest Match in Practice

- In general: lookahead of arbitrary length required
  - that is, $|v|$ unbounded in configurations (T, vqw, W)
  - see Example 3.19: $\alpha_1 = a$, $\alpha_2 = a^*b$, $w = a \dots a$
- "Modern" programming languages (Pascal, Java, ...): lookahead of one or two characters sufficient
  - separation of keywords, identifiers, etc. by spaces
  - Pascal: two-character lookahead required to distinguish `1.5` (real number) from `1..5` (integer range)

However: principle of longest match not always applicable!

Inadequacy of Longest Match I

Example 4.1 (Longest match in FORTRAN)

1. Relational expressions
   - valid lexemes: `.EQ.` (relational operator), `EQ` (identifier), `12` (integer), `12.`, `.12` (reals)
   - input string: `12␣.EQ.␣12` ⇝ `12.EQ.12` (ignoring blanks!)

Inadequacy of Longest Match I

Example 4.1 (Longest match in FORTRAN)

1. Relational expressions
   - valid lexemes: `.EQ.` (relational operator), `EQ` (identifier), `12` (integer), `12.`, `.12` (reals)
   - input string: `12␣.EQ.␣12` $\rightsquigarrow$ `12.EQ.12` (ignoring blanks!)
   - intended analysis: $(\mathrm{int}, 12)(\mathrm{relop}, \mathrm{eq})(\mathrm{int}, 12)$

Inadequacy of Longest Match I

Example 4.1 (Longest match in FORTRAN)

1. Relational expressions
   - valid lexemes: `.EQ.` (relational operator), `EQ` (identifier), `12` (integer), `12.`, `.12` (reals)
   - input string: `12␣.EQ.␣12` ⇝ `12.EQ.12` (ignoring blanks!)
   - intended analysis: (int, 12)(relop, eq), (int, 12)
   - LM yields: (real, 12.0)(id, `EQ`)(real, 0.12)

⇒ wrong interpretation

Inadequacy of Longest Match I

Example 4.1 (Longest match in FORTRAN)

1. Relational expressions
   - valid lexemes: `.EQ.` (relational operator), `EQ` (identifier), `12` (integer), `12.`, `.12` (reals)
   - input string: `12␣.EQ.␣12` ⇝ `12.EQ.12` (ignoring blanks!)
   - intended analysis: (int, 12)(relop, eq), (int, 12)
   - LM yields: (real, 12.0)(id, `EQ`)(real, 0.12)

   ⇒ wrong interpretation
2. `DO` loops
   - (correct) input string: `DO␣5␣I␣=␣1,␣20` ⇝ `DO5I=1,20`

Inadequacy of Longest Match I

Example 4.1 (Longest match in FORTRAN)

1. Relational expressions
   - valid lexemes: `.EQ.` (relational operator), `EQ` (identifier), `12` (integer), `12.`, `.12` (reals)
   - input string: `12␣.EQ.␣12` ⇝ `12.EQ.12` (ignoring blanks!)
   - intended analysis: (int, 12)(relop, eq), (int, 12)
   - LM yields: (real, 12.0)(id, `EQ`)(real, 0.12)

   ⇒ wrong interpretation
2. `DO` loops
   - (correct) input string: `DO␣5␣I␣=␣1,␣20` ⇝ `DO5I=1,20`
     - intended analysis:
       (do,)(label, 5)(id, `I`)(gets,)(int, 1)(comma,)(int, 20)

Inadequacy of Longest Match I

Example 4.1 (Longest match in FORTRAN)

1. Relational expressions
   - valid lexemes: `.EQ.` (relational operator), `EQ` (identifier), `12` (integer), `12.`, `.12` (reals)
   - input string: `12␣.EQ.␣12` ⇝ `12.EQ.12` (ignoring blanks!)
   - intended analysis: (int, 12)(relop, eq), (int, 12)
   - LM yields: (real, 12.0)(id, `EQ`)(real, 0.12)

   ⇒ wrong interpretation
2. `DO` loops
   - (correct) input string: `DO␣5␣I␣=␣1,␣20` ⇝ `DO5I=1,20`
     - intended analysis:
       (do,)(label, 5)(id, `I`)(gets,)(int, 1)(comma,)(int, 20)
     - LM analysis (wrong): (id, `DO5I`)(gets,)(int, 1)(comma,)(int, 20)

Inadequacy of Longest Match I

Example 4.1 (Longest match in FORTRAN)

1. Relational expressions
   - valid lexemes: `.EQ.` (relational operator), `EQ` (identifier), `12` (integer), `12.`, `.12` (reals)
   - input string: `12␣.EQ.␣12` ⇝ `12.EQ.12` (ignoring blanks!)
   - intended analysis: (int, 12)(relop, eq), (int, 12)
   - LM yields: (real, 12.0)(id, `EQ`)(real, 0.12)

   ⇒ wrong interpretation
2. `DO` loops
   - (correct) input string: `DO␣5␣I␣=␣1,␣20` ⇝ `DO5I=1,20`
     - intended analysis: (do,)(label, 5)(id, `I`)(gets,)(int, 1)(comma,)(int, 20)
     - LM analysis (wrong): (id, `DO5I`)(gets,)(int, 1)(comma,)(int, 20)
   - (erroneous) input string: `DO␣5␣I␣=␣1.␣20` ⇝ `DO5I=1.20`
     - LM analysis (correct): (id, `DO5I`)(gets,)(real, 1.2)

Inadequacy of Longest Match II

Example 4.2 (Longest match in C)

- valid lexemes:
  - `x` (identifier)
  - `=-` (decrement operator; ANSI-C: `-=`)
  - `1`, `-1` (integers)
- input string: `x=-1`

Inadequacy of Longest Match II

Example 4.2 (Longest match in C)

- valid lexemes:
  - `x` (identifier)
  - `=-` (decrement operator; ANSI-C: `-=`)
  - `1`, `-1` (integers)
- input string: `x=-1`
- intended analysis: $(\mathrm{id}, x)(\mathrm{gets},)(\mathrm{int}, -1)$

Inadequacy of Longest Match II

Example 4.2 (Longest match in C)

- valid lexemes:
  - `x` (identifier)
  - `=-` (decrement operator; ANSI-C: `-=`)
  - `1`, `-1` (integers)
- input string: `x=-1`
- intended analysis: $(\mathsf{id}, \mathtt{x})(\mathsf{gets},), (\mathsf{int}, -1)$
- LM yields: $(\mathsf{id}, \mathtt{x})(\mathsf{dec},)(\mathsf{int}, 1)$

⇒ wrong interpretation

Inadequacy of Longest Match II

Example 4.2 (Longest match in C)

- valid lexemes:
  - `x` (identifier)
  - `=-` (decrement operator; ANSI-C: `-=`)
  - `1`, `-1` (integers)
- input string: `x=-1`
- intended analysis: $(\mathrm{id}, x)(\mathrm{gets},), (\mathrm{int}, -1)$
- LM yields: $(\mathrm{id}, x)(\mathrm{dec},)(\mathrm{int}, 1)$

$\Rightarrow$ wrong interpretation

Possible solutions:

- Hand-written (non-FLM) scanners
- FLM with lookahead (later)

Outline

Regular Definitions I

Goal: modularizing the representation of regular sets by introducing additional identifiers

Regular Definitions I

Goal: modularizing the representation of regular sets by introducing additional identifiers

Definition 4.3 (Regular definition)

Let $\{R_1, \ldots, R_n\}$ be a set of symbols disjoint from Ω. A regular definition (over Ω) is a sequence of equations

$$\begin{aligned} R_1 &= \alpha_1 \\ &\vdots \\ R_n &= \alpha_n \end{aligned}$$

such that, for every $i \in [n]$, $\alpha_i \in RE_{\Omega \uplus \{R_1,\ldots,R_{i-1}\}}$.

Regular Definitions I

Goal: modularizing the representation of regular sets by introducing additional identifiers

Definition 4.3 (Regular definition)

Let $\{R_1, \ldots, R_n\}$ be a set of symbols disjoint from Ω. A regular definition (over Ω) is a sequence of equations

$$\begin{aligned} R_1 &= \alpha_1 \\ &\vdots \\ R_n &= \alpha_n \end{aligned}$$

such that, for every $i \in [n]$, $\alpha_i \in RE_{\Omega \uplus \{R_1,\ldots,R_{i-1}\}}$.

Remark: since recursion is not involved, every R_i can (iteratively) be substituted by a regular expression $\alpha \in RE_\Omega$
(otherwise $\Longrightarrow$ context-free languages)

Regular Definitions II

Example 4.4 (Symbol classes in Pascal)

Identifiers:

$$\begin{aligned}
\mathit{Letter} &= \texttt{A} \mid \ldots \mid \texttt{Z} \mid \texttt{a} \mid \ldots \mid \texttt{z} \\
\mathit{Digit} &= \texttt{0} \mid \ldots \mid \texttt{9} \\
\mathit{Id} &= \mathit{Letter}\,(\mathit{Letter} \mid \mathit{Digit})^*
\end{aligned}$$

Numerals: (unsigned)

$$\begin{aligned}
\mathit{Digits} &= \mathit{Digit}^+ \\
\mathit{Empty} &= \emptyset^* \\
\mathit{OptFrac} &= \texttt{.}\,\mathit{Digits} \mid \mathit{Empty} \\
\mathit{OptExp} &= \texttt{E}\,(\texttt{+} \mid \texttt{-} \mid \mathit{Empty})\,\mathit{Digits} \mid \mathit{Empty} \\
\mathit{Num} &= \mathit{Digits}\ \mathit{OptFrac}\ \mathit{OptExp}
\end{aligned}$$

Rel. operators:

$$\mathit{RelOp} = \texttt{<} \mid \texttt{<=} \mid \texttt{=} \mid \texttt{<>} \mid \texttt{>} \mid \texttt{>=}$$

Keywords:

$$\begin{aligned}
\mathit{If} &= \texttt{if} \\
\mathit{Then} &= \texttt{then} \\
\mathit{Else} &= \texttt{else}
\end{aligned}$$

Outline

The [f]lex Tool

Usage of [f]lex ("[fast] lexical analyzer generator"):

spec.l $\xrightarrow{\texttt{[f]lex}}$ lex.yy.c $\xrightarrow{\texttt{cc}}$ a.out

[f]lex specification — Scanner (in C) — Executable

Program $\xrightarrow{\texttt{a.out}}$ Symbol sequence

The [f]lex Tool

Usage of [f]lex ("[fast] lexical analyzer generator"):

$$\underset{\text{[f]lex specification}}{\texttt{spec.l}} \xrightarrow{\texttt{[f]lex}} \underset{\text{Scanner (in C)}}{\texttt{lex.yy.c}} \xrightarrow{\texttt{cc}} \underset{\text{Executable}}{\texttt{a.out}}$$

$$\text{Program} \xrightarrow{\texttt{a.out}} \text{Symbol sequence}$$

A [f]lex specification is of the form

Definitions (optional)
%%
Rules
%%
Auxiliary procedures (optional)

[f]lex Specifications

Definitions:

- C code for declarations etc.: *%{ Code %}*
- Regular definitions: *Name RegExp* ...
  (non-recursive!)

[f]lex Specifications

Definitions:
- C code for declarations etc.: %{ *Code* %}
- Regular definitions: *Name RegExp* ...
  (non-recursive!)

Rules: of the form *Pattern* { *Action* }

- *Pattern*: regular expression, possibly using *Name*s
- *Action*: C code for computing
  symbol = (token, attribute)
  - token: integer `return` value, 0 = `EOF`
  - attribute: passed in global variable `yylval`
  - lexeme: accessible by `yytext`
- matching rule found by FLM strategy
- lexical errors catched by `.` (any character)

Example [f]lex Specification

```
%{
  #include <stdio.h>
  typedef enum {EOF, IF, ID, RELOP, LT, ...} token_t;
  unsigned int yylval;   /* attribute values */
%}
LETTER      [A-Za-z]
DIGIT       [0-9]
ALPHANUM    {LETTER}|{DIGIT}
SPACE       [ \t\n]
%%
"if"                  { return IF; }
"<"                   { yylval = LT; return RELOP; }
{LETTER}{ALPHANUM}*   { yylval = install_id(); return ID; }
{SPACE}+              /* eat up whitespace */
.                     { fprintf (stderr, "Invalid character '%c'\n", yytext[0]); }
%%
int main(void) {
  token_t token;
  while ((token = yylex()) != EOF)
    printf ("(Token %d, Attribute %d)\n", token, yylval);
  exit (0);
}
unsigned int install_id () {...}   /* identifier name in yytext */
```

Regular Expressions in `[f]lex`

Syntax	Meaning
printable character	this character
`\n`, `\t`, `\123`, etc.	newline, tab, octal representation, etc.
`.`	any character except `\n`
[*Chars*]	one of *Chars*; ranges possible ("0-9")
[^*Chars*]	none of *Chars*
`\\`, `\.`, `\[`, etc.	`\`, `.`, `[`, etc.
"*Text*"	*Text* without interpretation of `.`, `[`, `\`, etc.
^α	α at beginning of line
$\alpha$$	α at end of line
{*Name*}	*RegExp* for *Name*
α?	zero or one α
α*	zero or more α
α+	one or more α
α{*n*, *m*}	between *n* and *m* times α (", *m*" optional)
(α)	α
$\alpha_1\alpha_2$	concatenation
$\alpha_1 \mid \alpha_2$	alternative
α_1/α_2	α_1 but only if followed by α_2 (lookahead)

Using the Lookahead Operator

Example 4.5 (Lookahead in FORTRAN)

1. `DO` loops (cf. Example 4.1)
   - input string: `DO 5 I = 1, 20`
   - LM yields: (id,)(gets,)(int, 1)(comma,)(int, 20)
   - observation: decision for do only possible after reading ","
   - specification of `DO` keyword in `[f]lex`, using lookahead:
     `DO / ({LETTER}|{DIGIT})* = ({LETTER}|{DIGIT})* ,`

Using the Lookahead Operator

Example 4.5 (Lookahead in FORTRAN)

1. `DO` loops (cf. Example 4.1)
   - input string: `DO 5 I = 1, 20`
   - LM yields: (id,)(gets,)(int, 1)(comma,)(int, 20)
   - observation: decision for do only possible after reading “`,`”
   - specification of `DO` keyword in `[f]lex`, using lookahead:
     `DO / ({LETTER}|{DIGIT})* = ({LETTER}|{DIGIT})* ,`
2. `IF` statement
   - problem: FORTRAN keywords not reserved
   - example: `IF(I,J) = 3` (assignment to an element of matrix `IF`)
   - conditional: `IF (`*condition*`) THEN ...` (with `IF` keyword)
   - specification of `IF` keyword in `[f]lex`, using lookahead:
     `IF / \( .* \) THEN`

Longest Match and Lookahead in [f]lex

```
%{
  #include <stdio.h>
  typedef enum {EoF, AB, A} token_t;
%}
%%
ab       { return AB; }
a/bc     { return A; }
.        { fprintf (stderr, "Invalid character '%c'\n", yytext[0]); }
%%
int main(void) {
  token_t token;
  while ((token = yylex()) != EoF) printf ("Token %d\n", token);
  exit (0);
}
```

Longest Match and Lookahead in [f]lex

```
%{
  #include <stdio.h>
  typedef enum {EoF, AB, A} token_t;
%}
%%
ab      { return AB; }
a/bc    { return A; }
.       { fprintf (stderr, "Invalid character '%c'\n", yytext[0]); }
%%
int main(void) {
  token_t token;
  while ((token = yylex()) != EoF) printf ("Token %d\n", token);
  exit (0);
}
```

returns on input

- a: `Invalid character 'a'`
- ab: `Token 1`
- abc: `Token 2  Invalid character 'b'  Invalid character 'c'`

$\Longrightarrow$ lookahead counts for length of match

Outline

Preprocessing

Preprocessing = preparation of source code before (lexical) analysis

Preprocessing steps

- macro substitution (`#define`)
- file inclusion (`#include`)
- conditional compilation (`#if`)
- elimination of comments